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**Effects of Specimen Preparation
on the Accuracy of Electromagnetic
Property Measurements of Solid
Materials With an Automatic
Network Analyzer**

Edward R. Long, Jr.

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Edward R. Long, Jr.
*Langley Research Center
Hampton, Virginia*



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Summary

Errors in specimen preparation for measurement of a material's electromagnetic properties at X_s -band microwave frequencies for the $TE_{1,0}$ mode have been studied. The measurement techniques utilize an automatic network analyzer and waveguide specimen holders. The importance of the following six parameters was investigated for an acrylic material: the ratio of specimen thickness to holder thickness, the gaps between the specimen and the walls of the holder, the accuracy in determining the thickness and position of the specimen, the roughness of the specimen surface, the nonuniformity of the specimen thickness, and the misalignment (canting) of the specimen in the holder. Acrylic was selected because it is relatively easy to prepare and the values of its electromagnetic properties are representative of most low-loss polymeric materials.

The parameter with the most significant effect on error was a gap between the specimen edge and the 0.901-in-wide wall of the specimen holder. (The cross section of the X-band waveguide is rectangular with inner dimensions of 0.901 and 0.401 in.) The thickness of this gap is in the direction of the 0.401-in-wide wall; therefore, the gap is referred to as being in the 0.401 direction. In order for the measurement error to be less than 1 percent, the gap in the 0.401 direction had to be less than 0.002 in. (0.5 percent of 0.401 in.). Thickness variations and alignment errors in the 0.901-in. direction equally had the next greatest effect on measurement accuracy. A taper of approximately 1.0° caused a 5-percent error in the measured permittivity, and a 1.0° error in alignment also caused a 5-percent error in the measured permeability. Errors in thickness measurement had the third most significant effect. A 3-percent error in the measurement of the thickness caused a 1-percent error in the permittivity measurement.

Of the other parameters, the following caused measurement errors of 1 percent or less: ratios of specimen thickness to holder thickness of 13 percent or more, gaps in the 0.901 direction of less than 0.045 in. (5 percent of 0.901 in.), position errors (in terms of specimen thickness) of 13 percent or less, surface roughness, thickness variation in the 0.401 direction of 35 percent or less, and specimen misalignment of 5° or less in the direction parallel to the 0.401-in. wall with respect to the waveguide direction.

For circumstances in which more than 1 percent error is acceptable (e.g., general surveys of trends in properties for large numbers of specimens), high precision in preparing a specimen is not required for measurement of a material's permittivity and

permeability. In most cases, high-precision specimen machining does not appear to be necessary.

Introduction

The automation of electrical network analyzers has greatly simplified measurement of transmission and reflection properties of materials and solid-state components and measurement of permittivity and permeability of materials over the frequency capability of the analyzer. Sample preparation has become a critical factor in determining how many measurements can be made within a given interval of time.

The purpose of this study is to evaluate the sensitivity of electromagnetic-property measurements of low-loss materials to the precision of specimen preparation. The specimens were of Plexiglas, an acrylic, which is a low-loss material. The Plexiglas was obtained in sheet form from Rohm and Haas Co. and was designated as Plexiglas II UVA, MIL-P-5425D, Finish A. Permittivity and permeability measurements were made with a computer-automated Hewlett-Packard Model 8409C Automatic Network Analyzer System. The studies were made in the X_s microwave frequency band, and waveguide specimen holders were used.

Experimental Arrangement

The arrangement for the permittivity and permeability measurements is shown in figure 1. The test section consisted of an X_s -band waveguide connected to the analyzer by a 7-mm coaxial cable, APC-7¹ connectors, high-quality coax-to-waveguide adaptors, and a waveguide specimen holder. The APC-7 connectors were tightened with a special-purpose torque wrench. The interfaces of all waveguide flanges were pin-aligned and, except for the interfaces between the specimen holder and the waveguide, were bolted together. Sheet metal clamps were used for the interfaces between the specimen holder and the waveguide.

Prior to measurements, the system was characterized and the characterization data stored and used to correct for imperfections in the measurement hardware and to establish a reference plane (RP). The characterization, which is a series of measurements in which an open, a short, and a sliding load are used, can be done with or without the specimen holder in place. (There is no specimen in the test section during the characterization.) Figure 2(a) shows the interface which became the reference plane for phase and amplitude for a characterization without

¹ APC-7 is a registered trademark of Bunker-Ramo Corporation.

the specimen holder. (An example of the sheet metal clamps used at the four corners of the interface is also shown.) If the specimen holder was a part of the characterization (fig. 2(b)), then the reference plane was either RP1 or RP2, depending on the procedure.

For either characterization configuration, there were errors caused when a specimen was introduced into the system; the errors were present irrespective of the care taken for each step of the characterization and measurement. For a characterization which did not include the specimen holder, the properties of the holder inner walls influenced the measured values. Also, the interface which existed during characterization (fig. 2(a)) was replaced by two new ones (fig. 2(b)) when the specimen holder was inserted for making a measurement. If, on the other hand, the specimen holder was included in the characterization, then the properties due to the imperfections in the holder were stored as part of the correction to a measurement, and the same interfaces existed. With the specimen in place, those properties caused by the holder imperfections were different from those stored during the characterization. For either of the characterization configurations, the introduction of a specimen changed the electrical length of the test section by an unknown amount. Consequently, the reference plane during a measurement of a specimen's electromagnetic properties was not at the same electrical position it was during the characterization. The resulting error was larger for a specimen having a larger reflectivity. However, for low-reflectivity specimens the dominant error source is the directivity of the couplers. (The performance characteristics for an HP Model 8409C Automatic Network Analyzer may be found in the systems operation and service manual. The errors are further reduced by the HP 11863E Accuracy Enhancement Pac, which is described in a separate Hewlett-Packard operation and programming manual.)

Electric-discharge machining (EDM) was used to fabricate the holders, whose thicknesses were appreciably more than those of the specimens. Figure 2(c) is a depiction of those holders. This method produced very precise-dimensioned holders which had extremely fine-textured, nondirectional inner walls. This finish did not affect the quality of the measurement when the specimen holder either was or was not a part of the characterization.

Parameters Studied

Among the experimental configuration parameters which can affect permittivity and permeability data are the ratio of specimen thickness to holder thickness, the gaps between the specimen and the

walls of the holder, the accuracy in determining specimen thickness and specimen position, the roughness of the specimen surface, the nonuniformity of specimen thickness, and the misalignment (canting) of the specimen in the holder. These parameters were individually varied and tested.

The data are normalized with respect to free-space values and are averages of values measured in 50-MHz steps from 8.0 to 12.5 GHz. The average real permittivity was determined to be 2.544. In comparison, the value averaged from midband data (from 9.55 to 10.05 GHz) was 2.548. However, measurements were not made more precisely than to two digits to the right of the decimal point; therefore, the value used for the real permittivity in this report is 2.54.

Results and Discussion

Specimen-Holder Thickness Ratio

The results for the holder being thicker than the specimen are shown in figure 3. The two thickest holders were fabricated by use of the EDM method whereas four others were made from flat flanges. The imaginary parts of the permittivity and permeability were zero, and the real part of the permeability was unity, as would be expected for acrylic.

The real permittivity values ranged from 2.52 (for a ratio of 15 percent) to 2.54 (for a ratio of 99 percent). This difference is less than 1 percent of the measured value and therefore indicates that a well-fabricated specimen holder, irrespective of its thickness, has little effect upon the value measured. The thickness may be more significant for highly reflective materials (those with a large dielectric constant).

Gaps

Two gaps are possible, one on the 0.401-in. side and one on the 0.901-in. side of the waveguide, as shown in figure 4. The effect of the gap depends on the propagation mode. For this study, the mode was TE_{1,0}; consequently, a gap on the 0.401-in. side (in 0.901 direction) would not have had as much effect because the parallel component of the electric field was zero at the wall. A gap on the 0.901-in. side (in 0.401 direction) would have had a larger effect because the electric field was not zero. Indeed, as shown in figure 5, this is what was observed. A gap of up to 0.041 in. in the 0.901 direction, which is 4.6 percent of 0.901 in., caused a change of 0.6 percent or less in the real permittivity. On the other hand, a 0.041-in. gap in the 0.401 direction, which is 10.2 percent of 0.401 in., caused a 10.85-percent change in the value of the real permittivity.

Therefore, for errors less than 1 percent the gap must be less than 0.040 in. (4.4 percent) in the 0.901 direction and less than 0.002 in. (0.5 percent) in the 0.401 direction. (For higher frequencies, such as K-band frequencies, the gaps probably follow the same limitations for the same mode of propagation and therefore would be correspondingly smaller than those found for the X-band case.) If, however, the tolerance of error is larger, such as may be the case for quick surveys, the specimen fit can be much less exacting.

Position and Thickness Errors

Incorrect values for position and thickness were input to the computer program to generate both position and thickness errors. The errors were computed from the exact thickness, as measured with a precision bench-top comparitor, and the exact position, as determined with a precision depth gauge.

The effect of position error on real relative permittivity is shown in figure 6. Samples of two thicknesses were used. Though there is some scatter, it is obvious that the measured permittivity varies with position error. However, even for a position error of 13 percent, the measurement error is less than 1 percent; therefore, considerable position error can be tolerated for all but the most exacting of measurements using a network analyzer. (For extremely thin specimens, such as films several thousandths of an inch thick, the accuracy which is required for measuring the position in order to maintain a position error of 13 percent or less may be as small as or less than the resolution of the measuring device. Consequently, there is a limit to thinness of the specimen for which the preceding statements are applicable.)

The effect of thickness error is shown in figure 7. A positive ratio of thickness error to thickness means a value for thickness was assigned which was greater than the actual thickness. Again, specimens of two thicknesses were studied. The permittivity values are much more sensitive to the thickness error than to the position error. In order to be within 1 percent of the specimen value of real permittivity, the thickness must be measured to within ± 3 percent of its actual value. For K_a-band measurements, specimens of materials with very high or small permittivities or very thin specimens of any material would require even more accuracy for the thickness measurements.

Surface Roughness

The surfaces of the acrylic specimens were very flat and smooth, typical of the finish when the protective paper covering is removed from a commercial

grade of acrylic sheet. The effect of surface roughness was evaluated by roughening the surface with dry silicon carbide abrasive paper.

Abrasive papers with three grit sizes were used: no. 400, no. 320, and no. 150. First, a specimen was measured with its original, smooth finish. Then it was successively roughened and remeasured. The thickness was also remeasured after each roughening operation. The value of the permittivity changed less than 0.1 percent. Therefore, specimens with considerable surface roughness will yield accurate property values.

Nonuniformity of Thickness

Precise tapers (as indicated for nonuniform-thickness specimen in fig. 8) at 1.0°, 2.5°, 5.0°, and 10.0° with respect to the waveguide wall were machined into specimens of various thicknesses to test the effects of nonuniformity of thickness. The specimen thickness was taken at the midpoint of the taper. Tapers were studied for both the 0.901 and the 0.401 direction.

Figure 9(a) indicates that the effect of the taper in the 0.901 direction was smaller for thicker specimens than for thin specimens and greater for larger angles than for smaller angles. In order to have errors in permittivity of less than 1 percent, specimens with thicknesses less than 0.20 in. must have a taper of less than 1.0°. The value for the real permeability also is affected, as shown in figure 9(b). The specimen was nonmagnetic, and therefore the permeability data clearly indicate measurement error if the specimen was nonuniform in the 0.901 direction.

The effects of taper at angles of 1.0°, 2.5°, 5.0°, and 10.0° in the 0.401 direction are shown in figures 10(a) and 10(b). The real permittivity is less than the reference value, that is, the change in the real relative permittivity is negative. The value of the permeability is different from that of a nonmagnetic material and, therefore, is again an immediate indication of error.

As the data indicate, variation of thickness in the 0.401 direction caused less error than variation in the 0.901 direction. A variation of 35 percent or less for specimens of 0.1-in. average thickness caused less than 1 percent change in the real permittivity value. This suggests that for measurements in which the full resolution capability of the network analyzer is not used, precise machining of specimen thickness is not necessary.

Misalignment (Canting)

Canting (shown in fig. 8(b)) was investigated for both the 0.901 and the 0.401 direction. Data for canting in the 0.901 direction are shown in figures 11(a)

and 11(b). For a given specimen thickness, increasing the canting caused a decrease in permittivity, the amount of which increased with thickness, and an increase in the permeability, the amount of which increased with thickness. The changes for permittivity were significant only for the 10.0° canting. The specimen could have been canted at an angle of as much as 5.0° without the permittivity error exceeding 1 percent. Thus, small errors in the direction of the surface normal are not important except for the most exacting of measurements. On the other hand, a 1.0° canting caused a 5-percent error in permeability for the thicker specimen. Even then, the error is at the threshold of the network analyzer's resolution capacity. Data for canting in the 0.401 direction are shown in figures 12(a) and 12(b). The effects of canting in the 0.401 direction were less significant, particularly for the permittivity. The permeability data do show some effects, but only for the thicker specimens.

Concluding Remarks

A study has been made of the effects of specimen preparation on the errors in measurements of a material's electromagnetic properties at X-band microwave frequencies. The measurement techniques utilize waveguide specimen holders and an automatic network analyzer. The data indicate that for general survey of trends of properties (for example, when measurement errors of more than 1 percent are acceptable), precision specimen preparation is not required. Consequently, acceptable survey evalua-

tions can be made within a time frame provided by rapid measurement capabilities of the analyzer without prolonged amount of time spent for specimen preparation.

If measurement errors less than 1 percent are required, then care must be given to the specimen preparation. At X-band frequencies the gap between the specimen and the 0.401-in. side of the waveguide had to be less than 0.002 in. In contrast, the gap between the specimen and the 0.901-in. side of the waveguide was 0.040 in. The error in measurement of specimen thickness could not exceed ± 3.0 percent. Variation in a specimen thickness in the 0.901-in. direction was important for specimens with a thickness less than 0.20 in. (For this material, this equates to an electrical length of 0.28 in.) For the 0.401-in. direction, the variation in thickness could be as much as 35 percent. The error in the specimen position, in terms of specimen thickness, could be as much as 13 percent. The specimen alignment with respect to the waveguide length had to be within 5° for an error in permittivity of less than 1 percent. Surface roughness of the specimen face did not appear to be important. The ratio of the specimen thickness to the length of the holder also did not appear to be critical if the holder interior surface had a nondirectional finish.

NASA Langley Research Center
Hampton, VA 23665-5225
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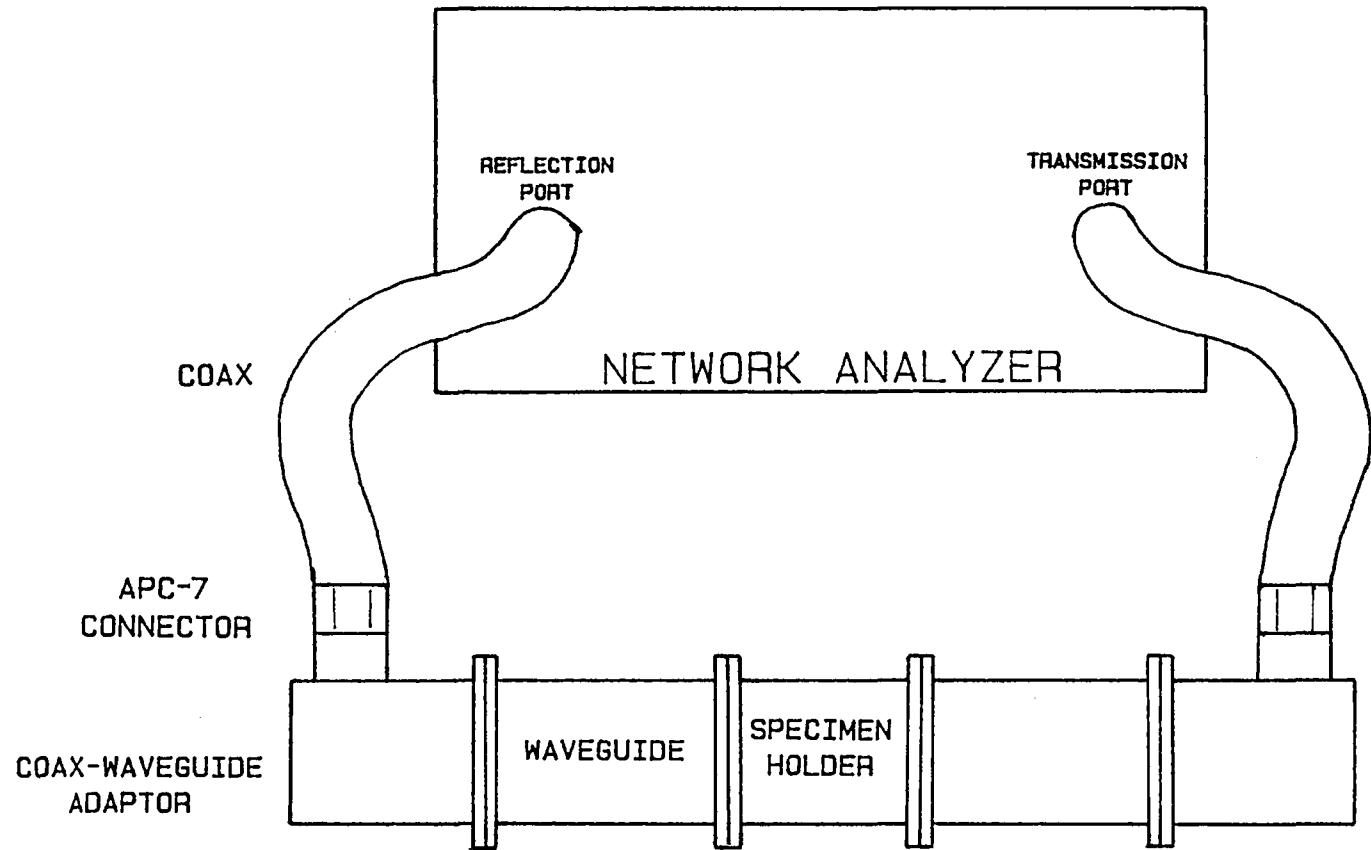


Figure 1. Configuration for use of network analyzer for measurement of electromagnetic properties of material in a waveguide.

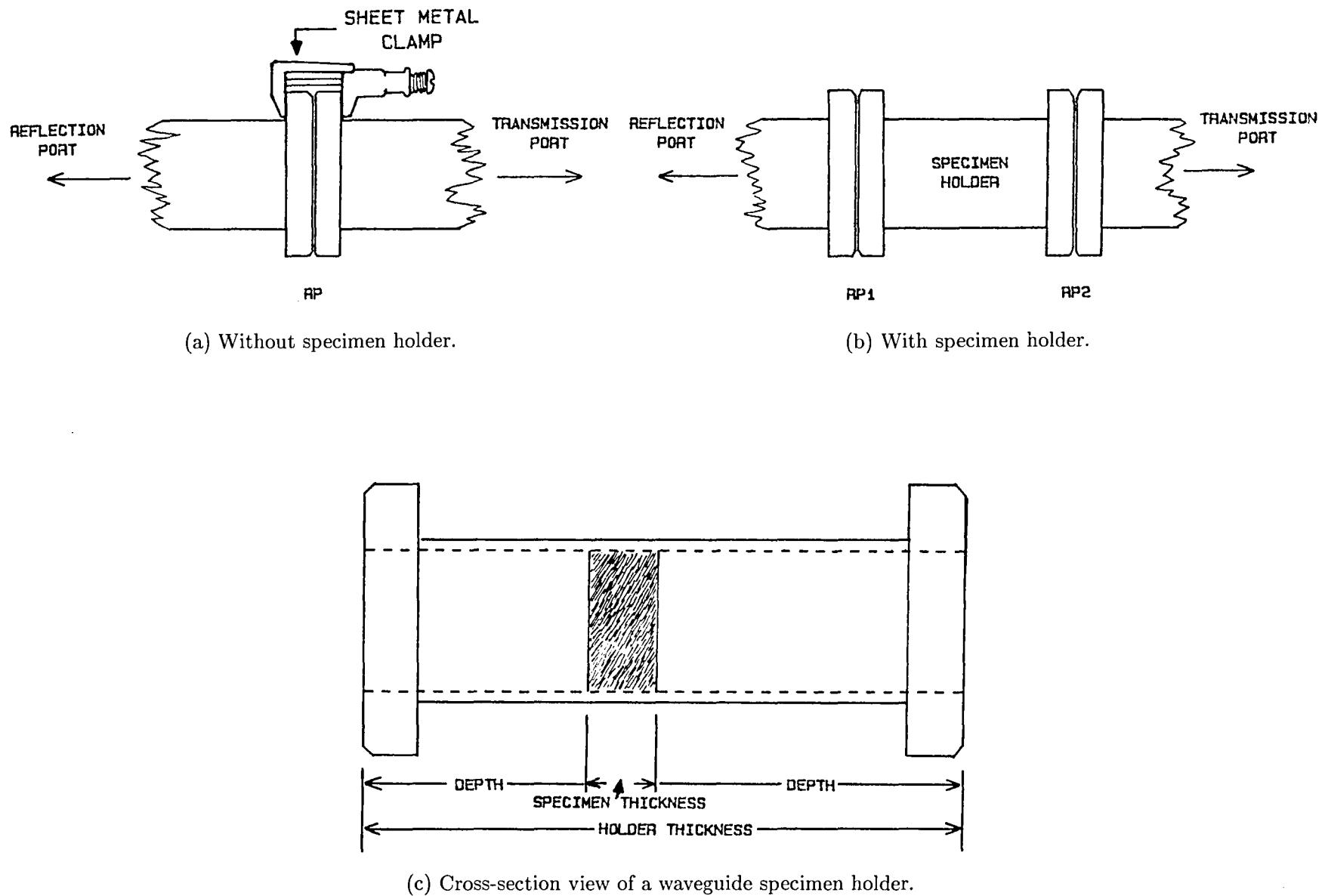


Figure 2. Configurations for characterization of the measurement system.

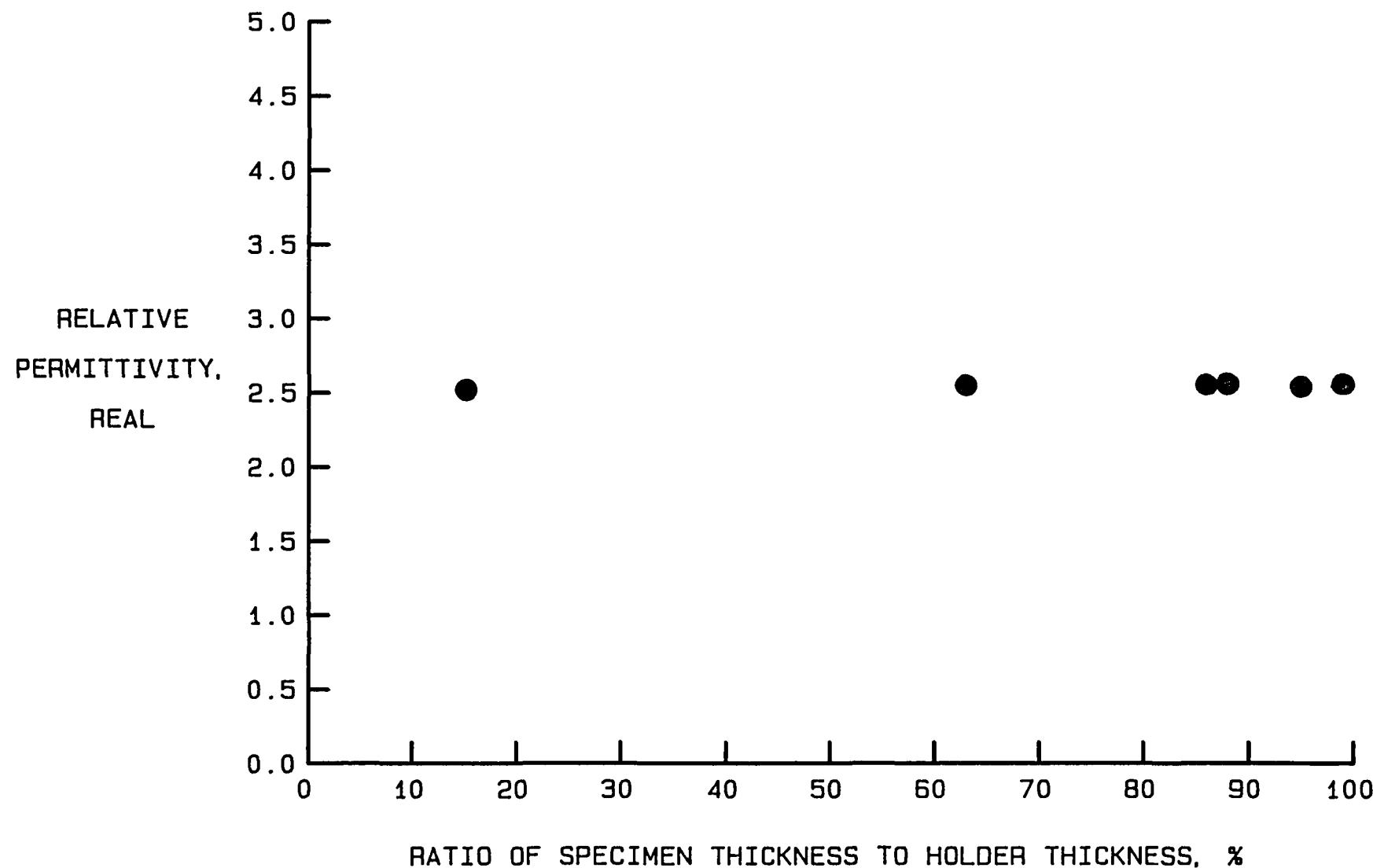
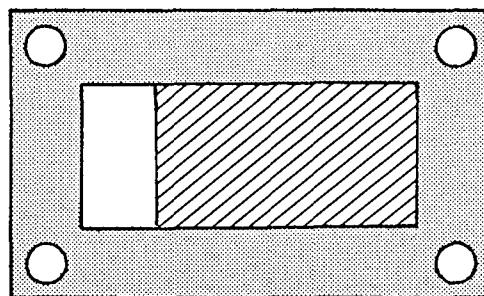
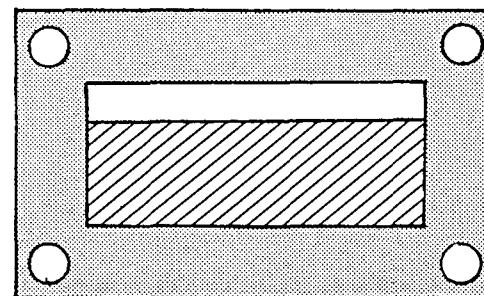


Figure 3. Real relative permittivity of acrylic for several specimen-holder thickness ratios.



GAP ON 0.401 SIDE
(IN 0.901 DIRECTION)



GAP ON 0.901 SIDE
(IN 0.401 DIRECTION)

Figure 4. Views along direction of waveguide showing two possible gaps which may occur between specimen edge and walls of waveguide holder. Dimensional quantities are in inches.

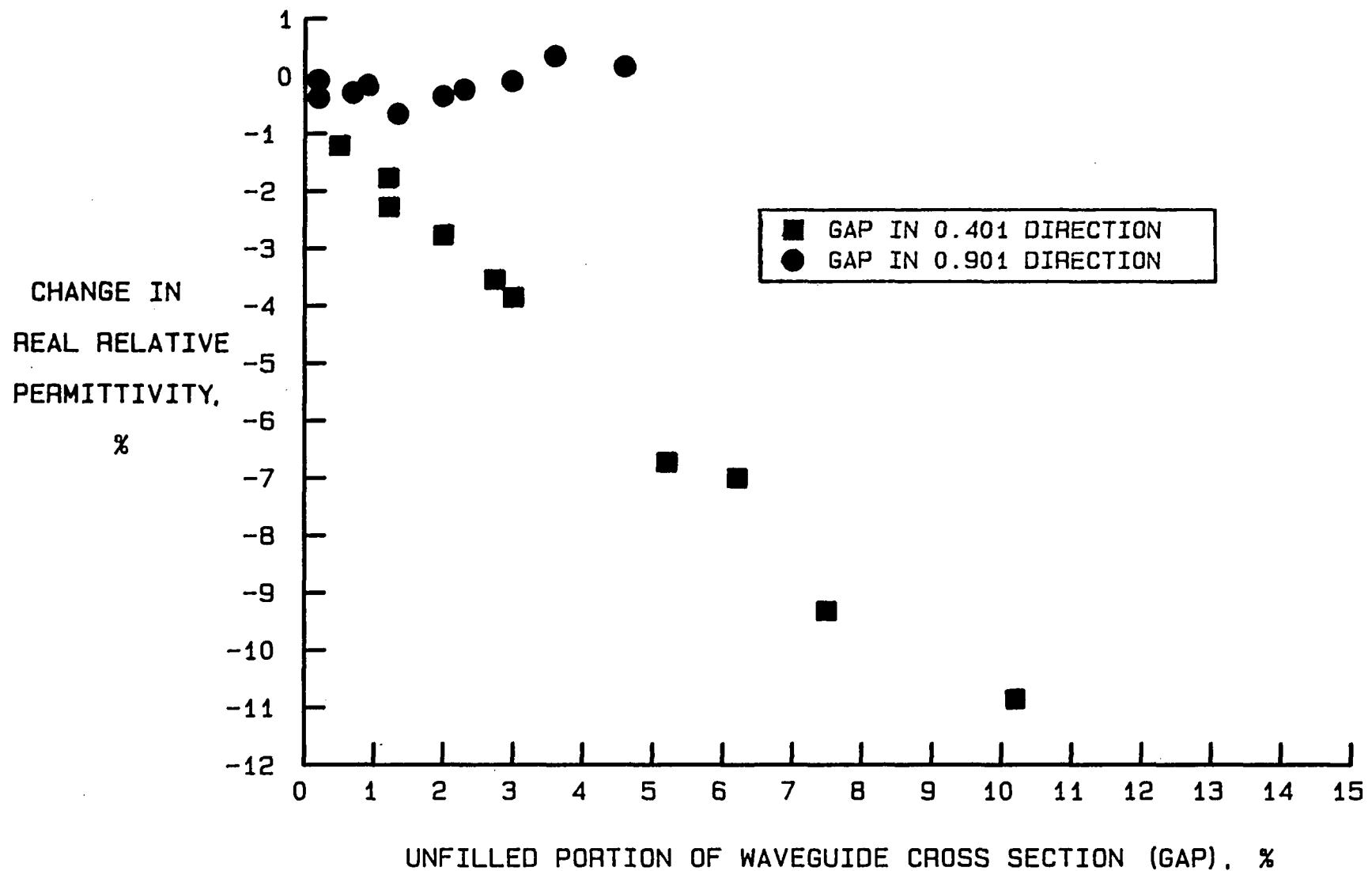


Figure 5. Percent change in measured real relative permittivity because of gaps between edge of specimen and walls of waveguide.

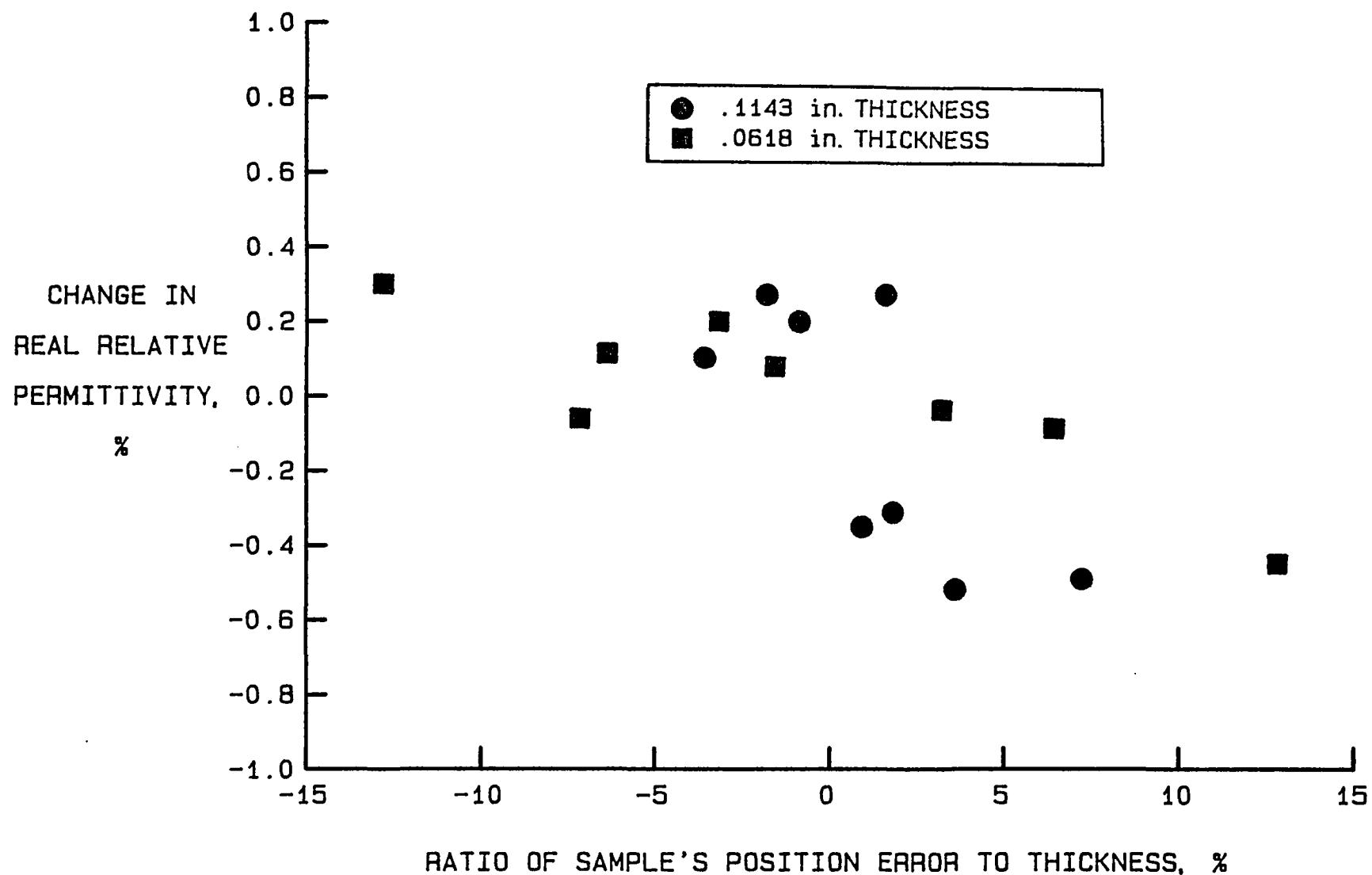


Figure 6. Percent change in measured real relative permittivity because of error in positioning specimen in waveguide. Error is expressed as percentage of specimen thickness.

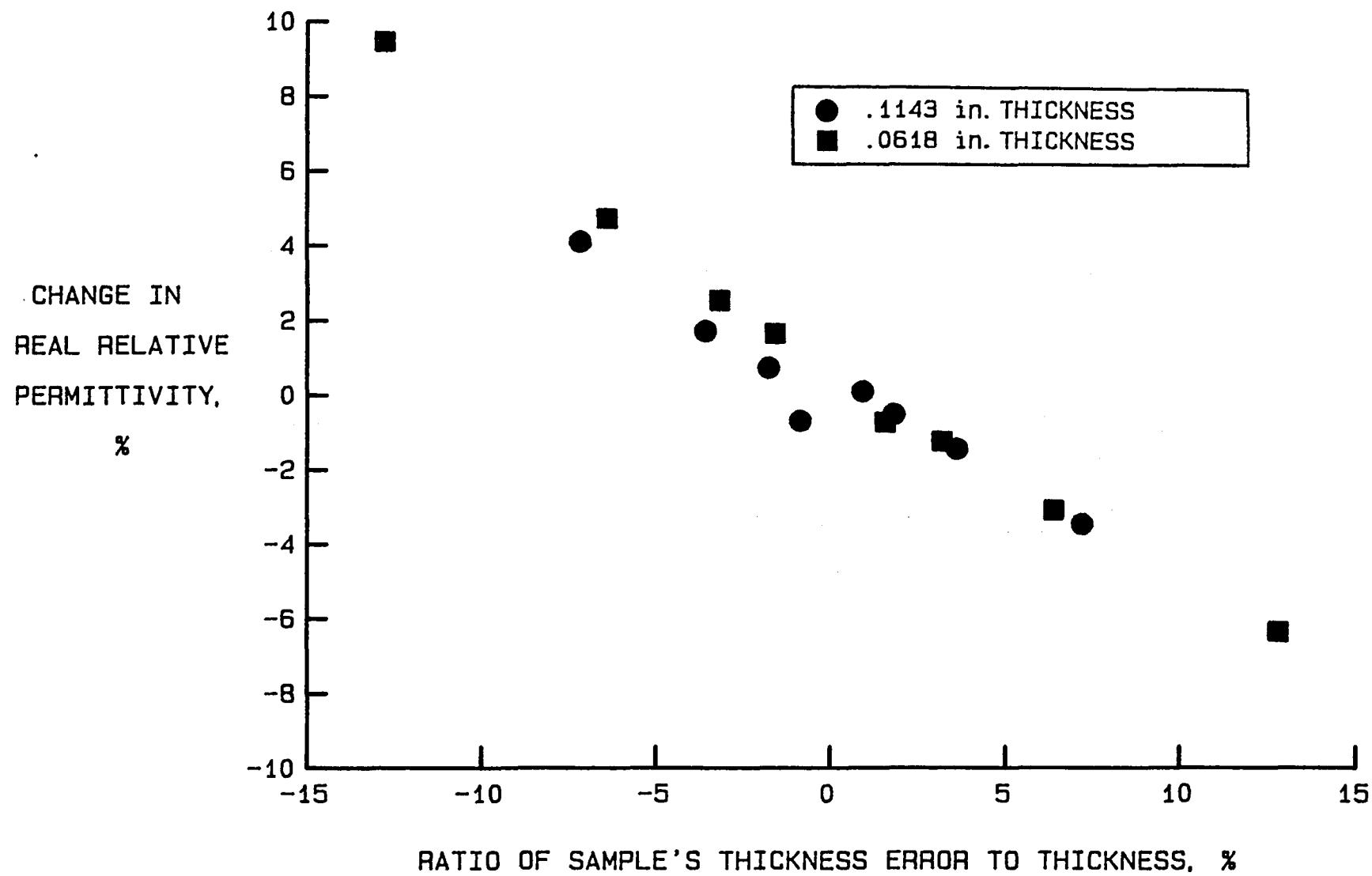
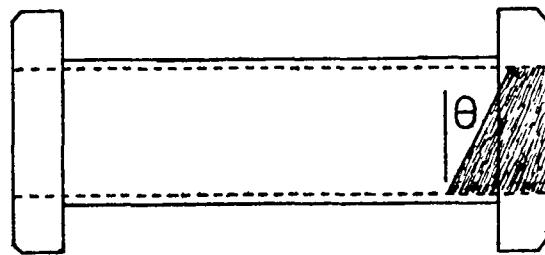
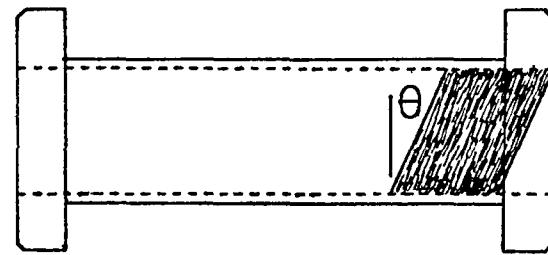


Figure 7. Percent change in measured real relative permittivity because of error in measurement of specimen thickness.

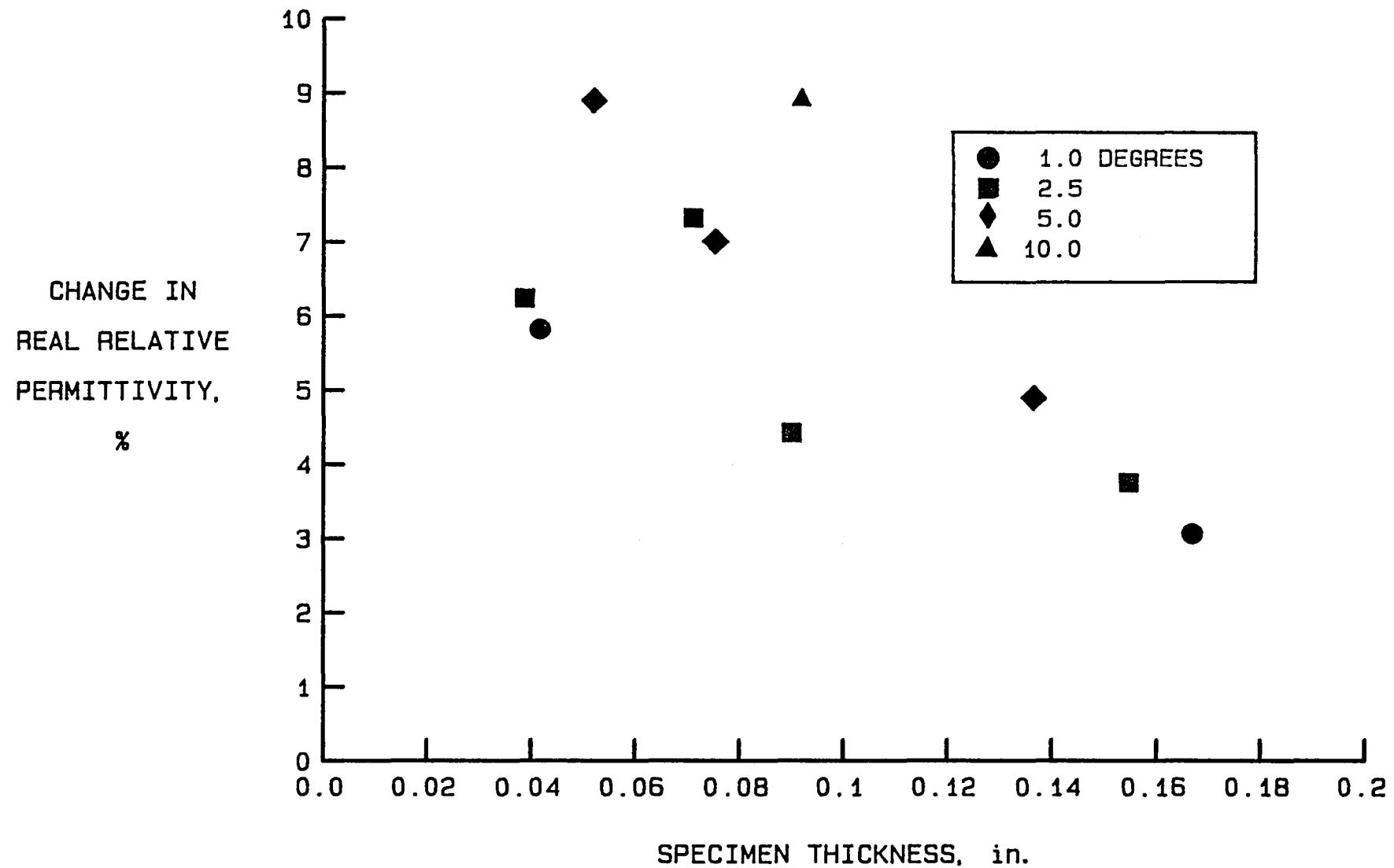


(a) Nonuniform thickness specimen.



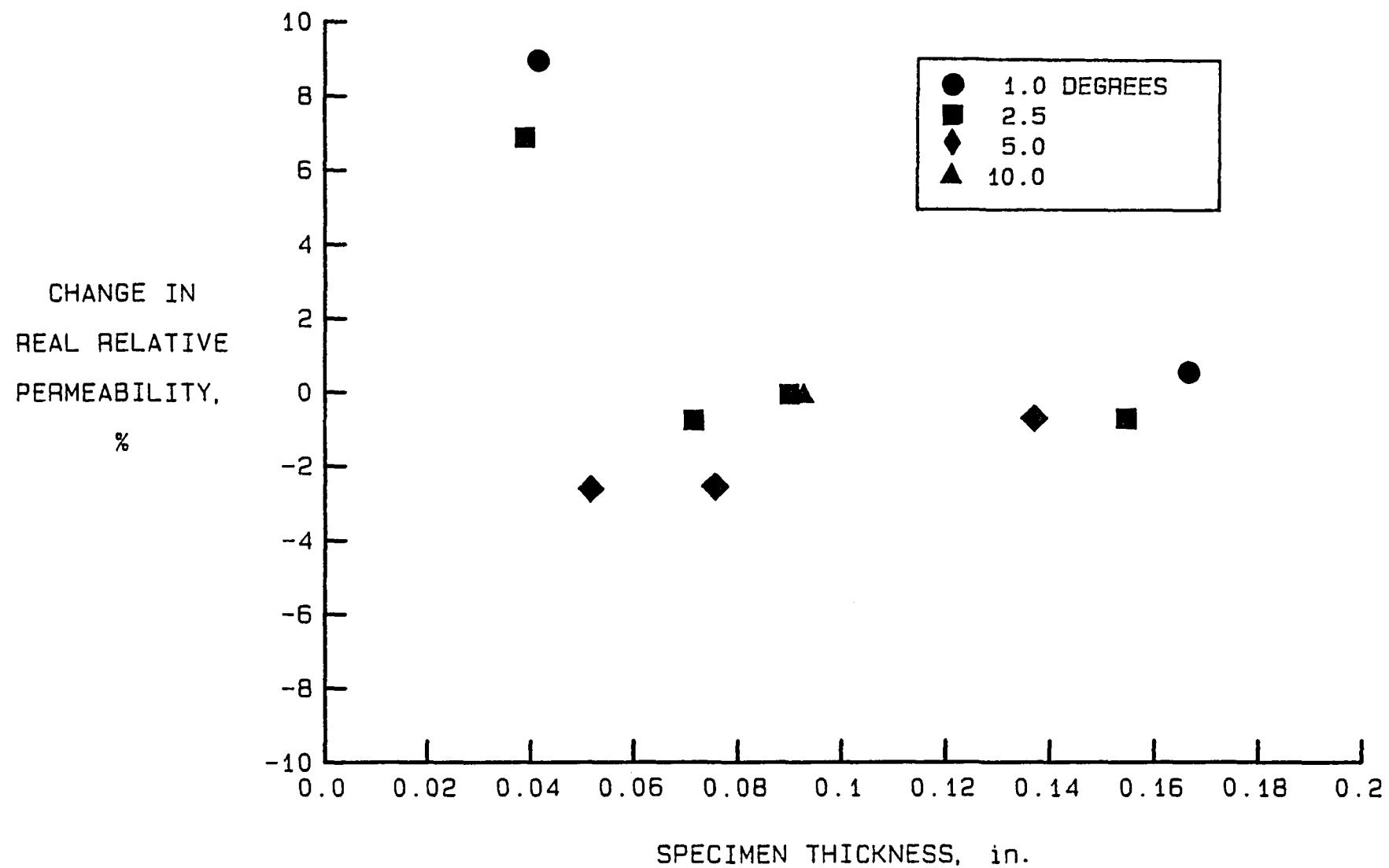
(b) Canted specimen.

Figure 8. Profile views of nonuniform-thickness and canted specimens. Direction with respect to which angle is measured is either 0.401 direction or 0.901 direction.



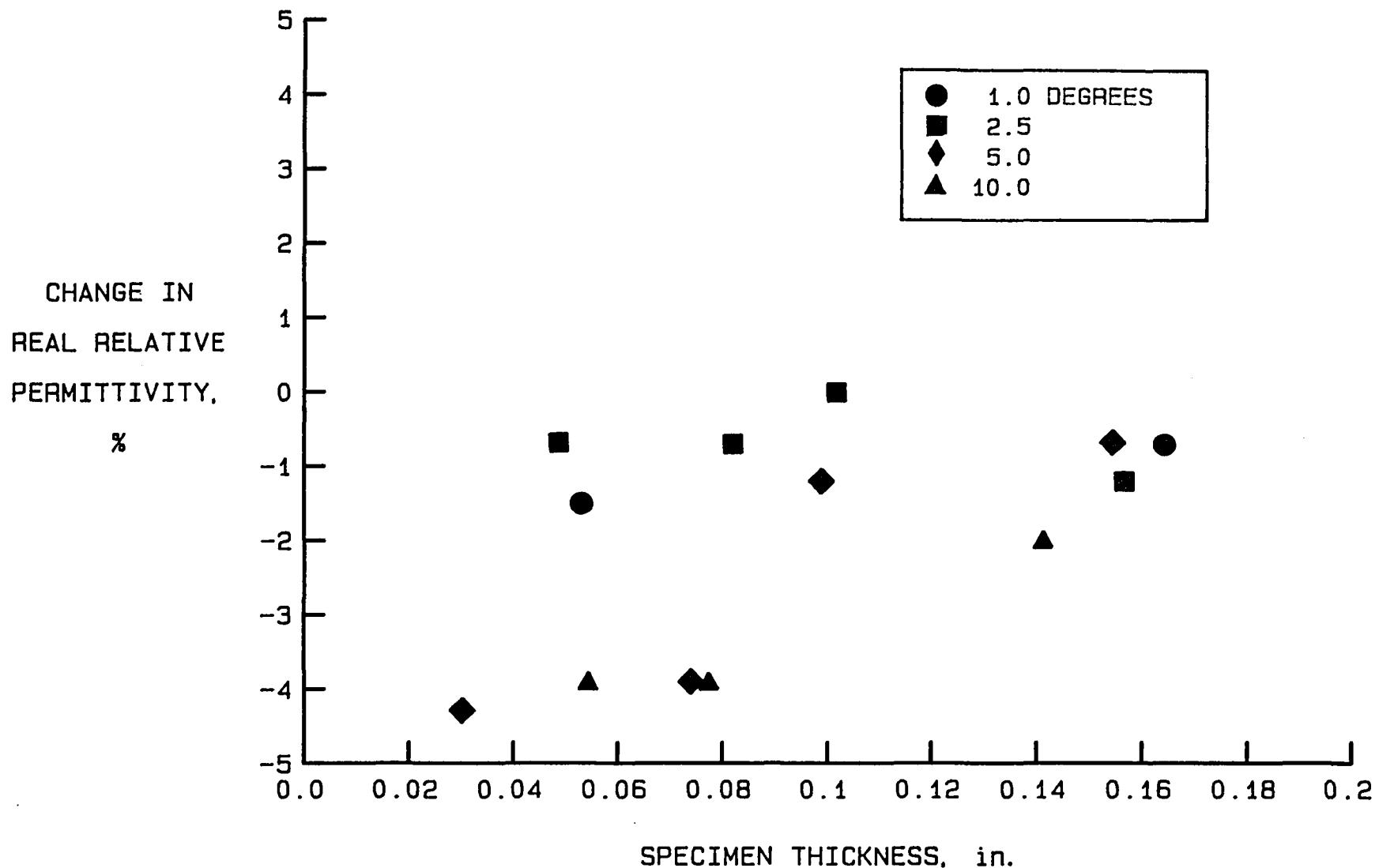
(a) Permittivity data.

Figure 9. Percent change in measured real relative permittivity and permeability because of specimen taper (nonuniform thickness) in 0.901 direction. Number of degrees refers to angle in figure 8(a).



(b) Permeability data.

Figure 9. Concluded.



(a) Permittivity.

Figure 10. Percent change in measured real relative permittivity and permeability because of specimen taper (nonuniform thickness) in 0.401 direction. Number of degrees refers to angle in figure 8(a).

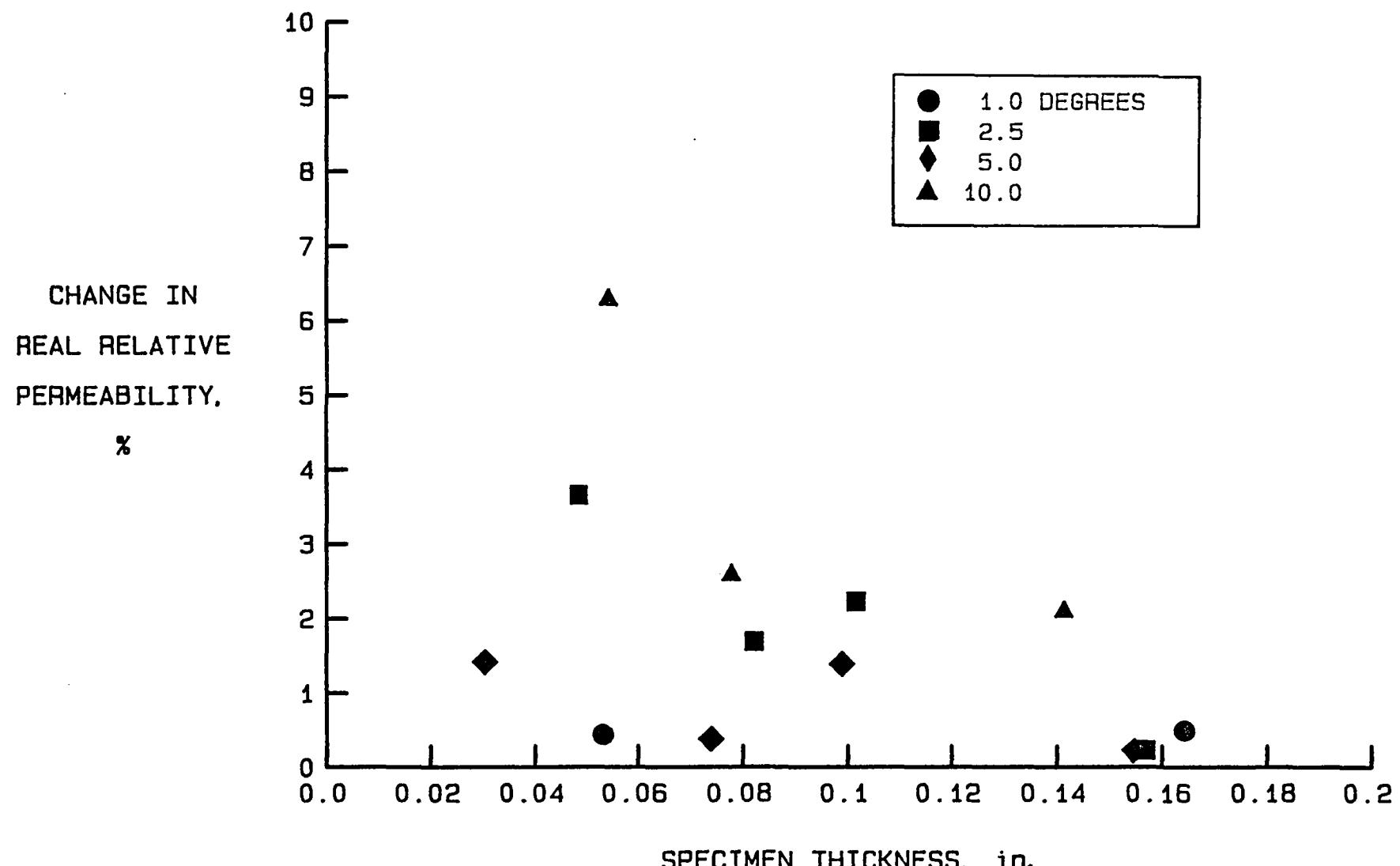
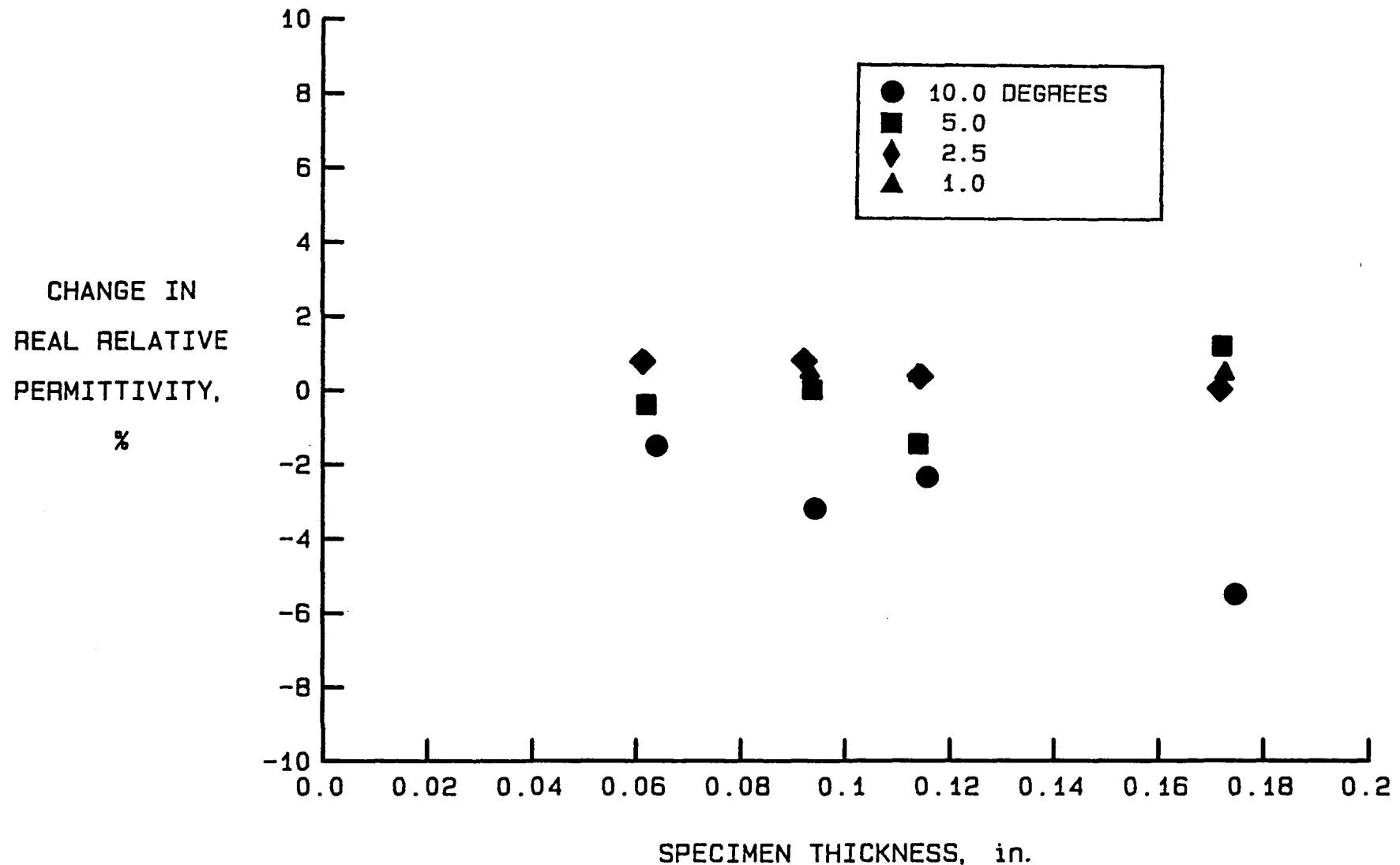
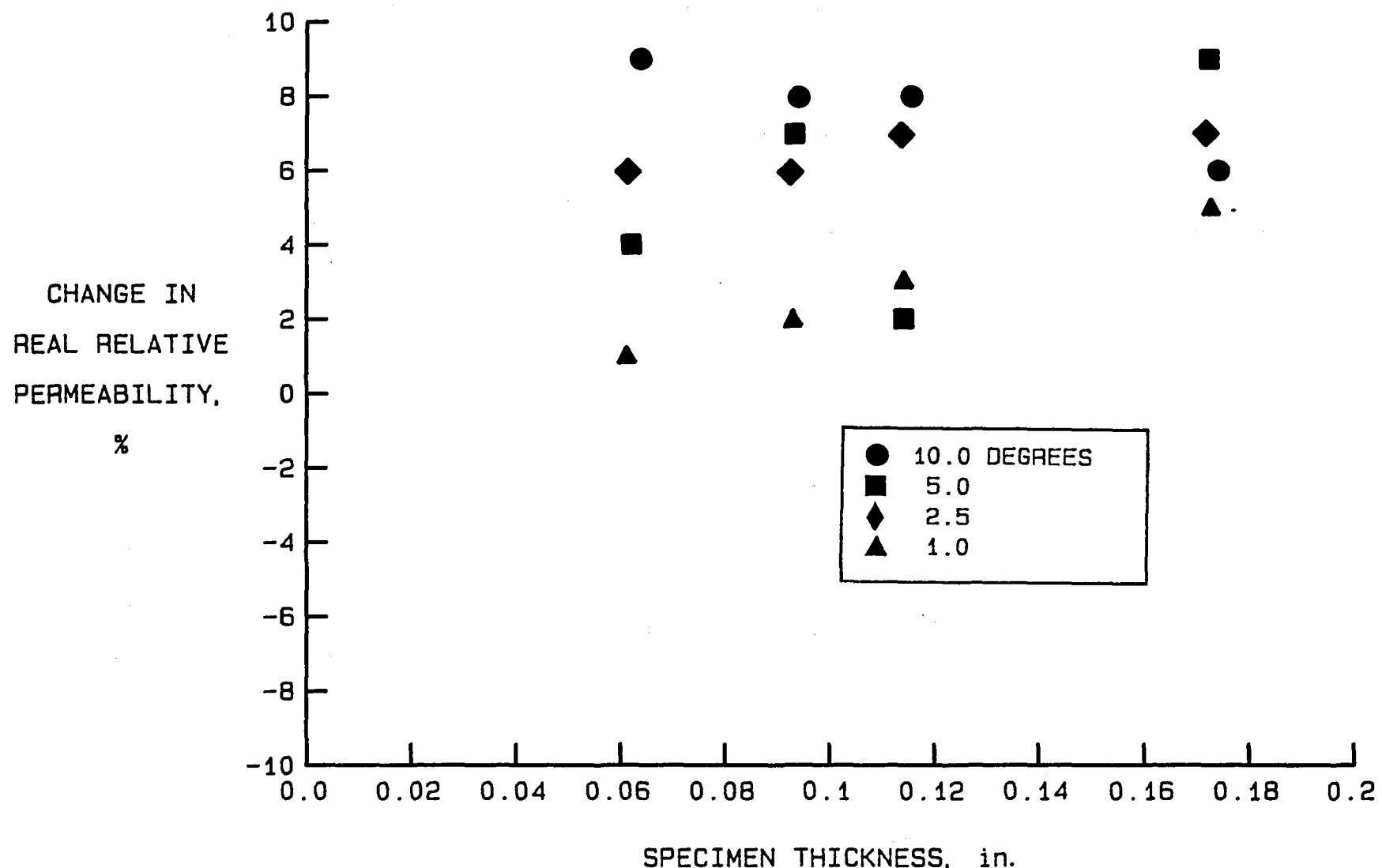


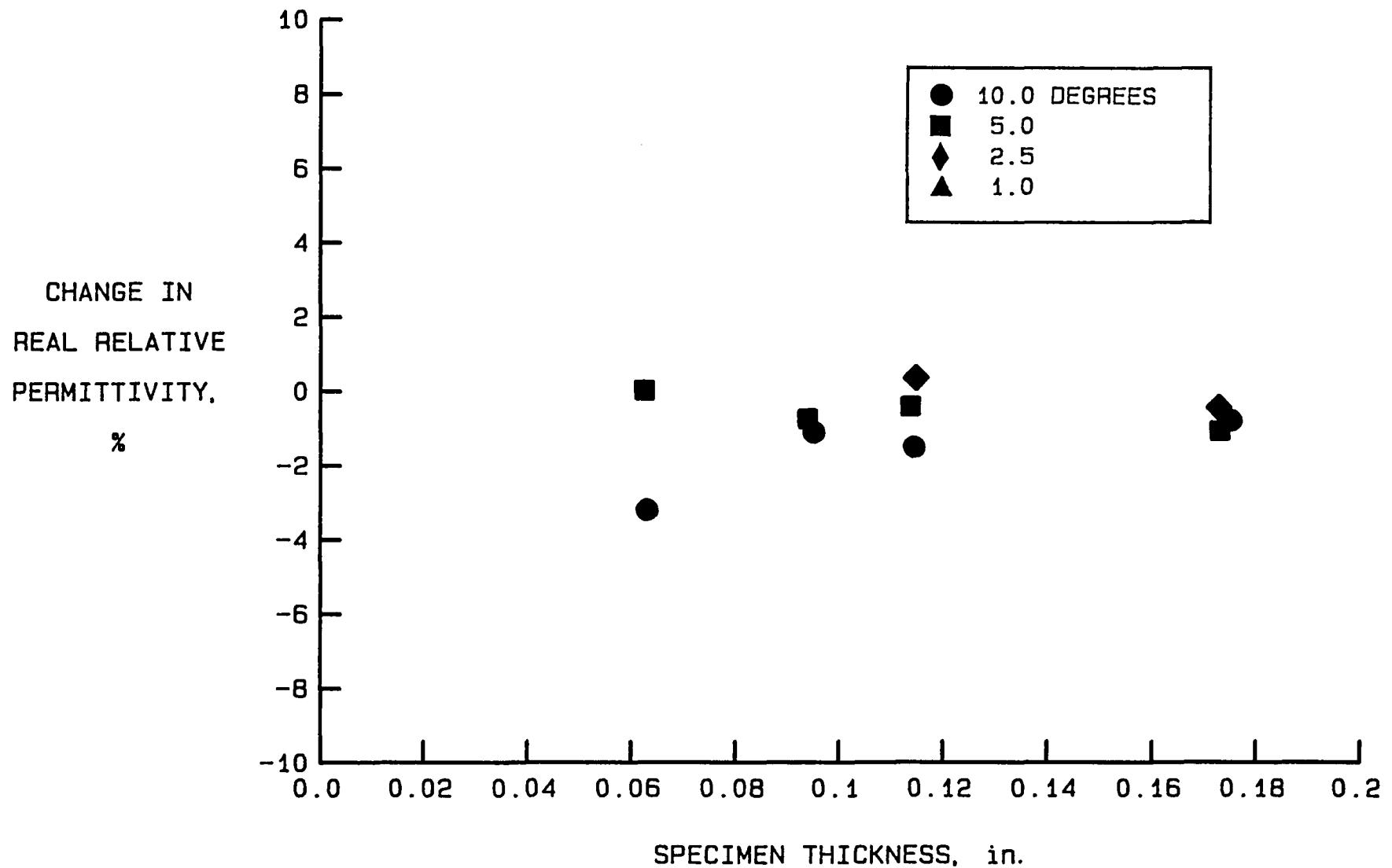
Figure 10. Concluded.



(a) Permittivity data.

Figure 11. Percent change in measured real relative permittivity and permeability because of canting (misalignment) of specimen with respect to 0.901 direction. Number of degrees refers to angle in figure 8(b).



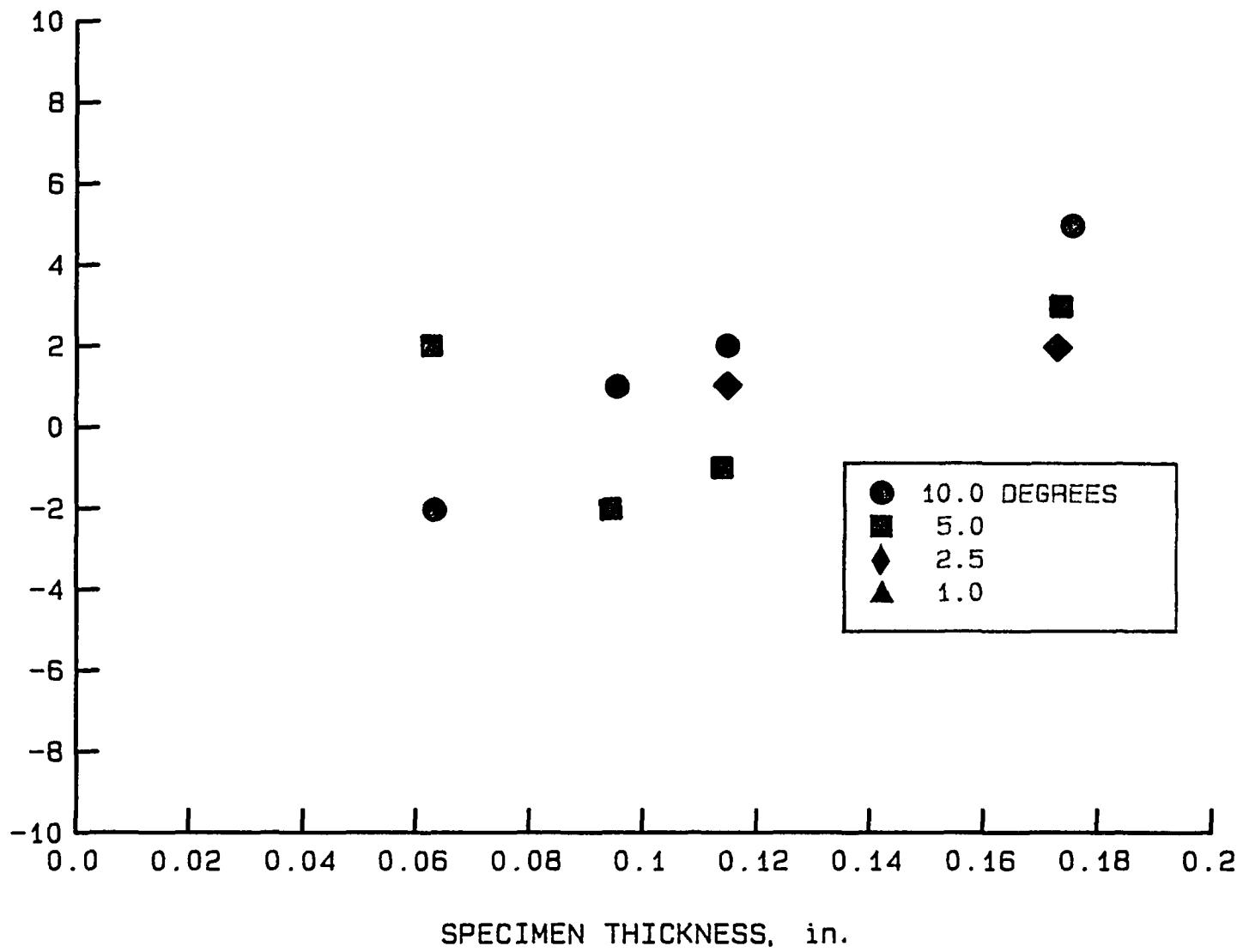


(a) Permittivity data.

Figure 12. Percent change in measured real relative permittivity and permeability because of canting (misalignment) of specimen with respect to 0.401 direction. Number of degrees refers to angle in figure 8(b).

CHANGE IN
REAL RELATIVE
PERMEABILITY,

%



(b) Permeability data.

Figure 12. Concluded.

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16. Abstract Effects of specimen preparation on measured values of an acrylic's electromagnetic properties at X-band microwave frequencies, TE _{1,0} mode, utilizing an automatic network analyzer have been studied. For 1 percent or less error, a gap between the specimen edge and the 0.901-in. wall of the specimen holder was the most significant parameter. The gap had to be less than 0.002 in. The thickness variation and alignment errors in the direction parallel to the 0.901-in. wall were equally second most significant and had to be less than 1°. Errors in the measurement of the thickness were third most significant. They had to be less than 3 percent. The following parameters caused errors of 1 percent or less: ratios of specimen-holder thicknesses of more than 15 percent, gaps between the specimen edge and the 0.401-in. wall less than 0.045 in., position errors less than 15 percent, surface roughness, thickness variation in the direction parallel to the 0.401-in. wall less than 35 percent, and specimen alignment in the direction parallel to the 0.401-in. wall less than 5°.				
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